Keck Imaging of Binary L Dwarfs

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ABSTRACT

We present Keck near-infrared imaging of three binary L dwarf systems, all of which are likely to be sub-stellar. Two are lithium dwarfs, and a third exhibits an L7 spectral type, making it the coolest binary known to date. All have component flux ratios near 1 and projected physical separations between 5 and 10 AU, assuming distances of 18 to 26 pc from recent measurements of trigonometric parallax. These surprisingly similar binaries represent the sole detections of companions in ten L dwarf systems which were analyzed in the preliminary phase of a much larger dual-epoch imaging survey. The detection rate prompts us to speculate that binary companions to L dwarfs are common, that similar-mass systems predominate, and that their distribution peaks at radial distances in accord both with M dwarf binaries and with the radial location of Jovian planets in our own solar system. To fully establish these conjectures against doubts raised by biases inherent in this small preliminary survey, however, will require quantitative analysis of a larger volume-limited sample which has been observed with high resolution and dynamic range.

Subject headings: stars: circumstellar matter — binaries: spectroscopic – planetary systems

1. Introduction

L dwarfs make up a new spectral class of objects that are believed to have masses near or below the hydrogen-burning limit (Kirkpatrick et al. 1999a; 1999b). Many satisfy currently accepted criteria for identification as *bona fide* brown dwarfs (See Tinney 1999 for a review). Their local field detection rate in infrared sky surveys suggests they comprise a sizeable population which is well represented by an extension of the field-star mass function, $\Psi(M) \propto M^{-\alpha}$, with $1 < \alpha < 2$ (Reid et al. 1999). The occurrence frequency of multiplicity among these systems is completely unknown; it is an open question as to whether the distribution of their companions matches that of M dwarfs or bears the stamp of a different, sub-stellar formation mechanism.

Stellar companions are detected in approximately 35% of M dwarf systems with a distribution peaking at a radius in the range $3 - 30$ AU (Fischer & Marcy 1992; Henry & McCarthy 1993; Reid & Gizis 1997). Efforts to uncover the mass and radial distribution of extra-solar planets around M stars are just beginning to meet with success and have revealed super Jovian-mass planets within a few AU of their central stars, consistent with results for earlier spectral types (Marcy et al. 1998). The relationship of this population to that of binary companions and planetary systems like our own is a topic of current debate (Black 1997). The true answer will not be readily apparent until a more complete range of mass and orbital distances has been surveyed. Ground-based imaging of L dwarfs provides a unique piece to this puzzle, since the reduced glare of low-luminosity primaries affords increased sensitivity to very faint companions.

To date, very few multiple L dwarf systems have been identified. Several L dwarf secondaries have been discovered around nearby stars (Becklin & Zuckerman 1988; Rebolo et al. 1998; Kirkpatrick et al. 1999b). Among a handful of binary systems believed to be composed of two brown-dwarf components (e.g., Basri & Martín 1997), only two have

primary spectral types as late as L: 2MASSW J0345 is a double-lined spectroscopic L dwarf system (Reid et al. 1999), and DENIS-P J1228 was shown to be double in HST imaging observations (Martín et al. 1999). The latter is composed of equal-luminosity components with a projected separation of $0.275''$ (5 AU at the 18 pc distance of DENIS-P J1228).

Here we present the first results of a Keck near-infrared imaging survey of a large sample of L dwarfs. At a projected distance of a few AU, our program is capable of detecting companions with luminosity similar to the primary. At further projected distances, our survey is sensitive to objects which are several magnitudes fainter than the methane brown dwarf, Gl 229B. In this work, we report the K-band detection of three L dwarf binaries, including DENIS-P J1228.

2. Observations

Our target sample was culled from the 2MASS and DENIS near-infrared sky surveys and consisted of objects spectroscopically confirmed to be L dwarfs. We also included observations of a smaller sample of nearby very late M dwarfs. Imaging was carried out at the Keck I telescope with NIRC, a cryogenically-cooled near-infrared camera that incorporates a 256×256 Indium-antimonide array at the f/25 focus in an optical framework which yields a $0.15''$ plate scale and $38''$-square field of view (Matthews & Soifer 1994). One-minute integrations were taken in the K-band filter at each of nine dithered positions separated by $5''$. Individual frames were flat-fielded and differenced, then shifted and combined to create a sensitive composite image suitable for detecting companions to a limiting magnitude of $m_K \approx 20$. At this level of sensitivity, several additional sources were typically detected in each frame. Repeat observations in a second epoch were taken one year or more later to determine if any of these share common proper motion with the target; second-epoch observations are complete for only a subset of the sample which includes 10 L

dwarfs at present. Analysis of the completed survey will be presented in a future work.

In addition to the common proper motion analysis of faint sources, we inspected the core of each of the primaries to search for extended emission associated with a marginally resolved binary. Second-epoch observations not only served to provide evidence of common proper motion, but also helped to ensure that any elongation was not due to time-dependent errors in phasing of the segmented primary mirror. Point-like sources observed nearby in the sky and within an hour of the target observations were chosen to serve as psf measurements. Dithered images of candidate binaries and psf stars were not shifted and combined but were treated as independent data sets. Psf stars were fit in duplicate to each of the candidate binary images using a least-squares minimization method. Typically, nine psf frames were fit to each of nine image frames for a total of 81 independent fits. Properties of the psf and target sources used in this work are listed in Table 1; results of the psf-fitting are given in Table 2.

3. Results

Three objects met our critieria for reliable identification of a true close binary system, i.e., the availability of suitable psf observations and consistent results in psf-fitting for at least two epochs. Contour plots of DENIS-P J1228, DENIS-P J0205, and 2MASSW J1146 are displayed in Fig. 1, together with the psf stars used to decompose them into separate components. The results of psf-fits in each epoch are listed in Table 2 and plotted in Fig. 2 and 3. Parameter estimates are consistent between two epochs; variations in the uncertainties are largely due to different seeing conditions. Conservatively, we state here the mean of the measurements in all epochs (rather than simply the best-seeing epoch) together with an uncertainty calculated as the root mean square difference from the mean. For the separation and PA of the component positions, these are plotted as large symbols in Fig. 2

and are $0.27 \pm 0.03''$, $0.51 \pm 0.03''$, $0.29 \pm 0.06''$ and $33 \pm 15°$, $92 \pm 18°$, $206 \pm 19°$ for the component separations and PA's of DENIS-P J1228, DENIS-P J0205, and 2MASSW J1146, respectively. Projected separations correspond to physical separations of 4.9, 9.2, and 7.6 AU at distances implied by parallaxes listed in Table 1. Histograms of the flux-component ratios are plotted in Fig. 3; mean values are 1.1 ± 0.4, 1.0 ± 0.4, and 1.0 ± 0.3.

DENIS-P J1228

DENIS-P J1228 was discovered by Delfosse et al. (1997) and shown to have lithium by Tinney et al. (1997) and Martín et al. (1997). It is an L5 V dwarf in the classification scheme of Kirkpatrick et al. (1999a) with a temperature less than 1700 K implied by the absence of Vanadium Oxide in its spectrum. Martín et al. (1999) first discovered the binary nature of DENIS-P J1228 and reported B/A flux ratios of 0.83, 0.86, and 0.87 in the HST/NICMOS filters, F110M, F135M, and F165M, respectively. Our K-band flux ratio for the same components, 1.1 ± 0.4, is consistent with a trend in the HST fluxes which implies that DENIS-P J1228B is slightly cooler, as is the value obtained on the best night of seeing, 0.99 ± 0.25.

The separation and PA reported by Martín et al. (1999) are plotted in Fig. 2 and were obtained in observations taken mid-way between Keck observations spaced one year apart. The results clearly agree over an observational period during which the system should have moved $0.21''$ along PA 143.8° according to measurements by Dahn et al. (1999) that are listed in Table 1. Indeed, we measure the mean proper motion with respect to background stars in our field as $\mu = 0.23 \pm 0.05''$ at PA $130.4 \pm 8°$. If either binary component is a background star, this would result in a later-epoch separation that is too large to be consistent with our observations. Thus DENIS-P J1228 is a true common proper motion binary.

A recently determined value of the trigonometric parallax for DENIS-P J1228 is listed

in Table 1 as 0.0553±0.0029″ and implies a distance of 18.1 ± 1.0 pc. This result agrees with the distance estimate of Martín et al. (1999), based on the spectroscopic parallax of Delfosse et al. (1997), and from which they derived a projected physical separation of 5 AU. Assuming circular orbits and masses of 0.05 $M_{\odot}$, they calculate that orbital motion can be detected by HST in one year. A precise determination of dynamical mass will require observations over a much larger fraction of an orbit, however. The orbital period is at least 35 years, so a highly refined mass estimate may not be forthcoming on timescales competitive with analysis of closer binaries discovered in the interim. Nevertheless, this binary has the smallest projected physical separation of those presented here, hence, the best opportunity for near-term estimates of the dynamical mass. The importance of such an observation is highlighted by the fact that, to date, secure dynamical mass determinations have barely begun to extend to masses below the hydrogen-burning limit (cf. Henry et al. 1999).

DENIS-P J0205

DENIS-P J0205 was first discovered by Delfosse et al. (1997) and is reported in Kirkpatrick et al. (1999a) as a prototype of the L7 V spectral class. Although no lithium line is evident in its spectrum, this may indicate a sufficiently cool temperature to foster depletion of atomic Li condensing out as LiCl. It is, in any case, the coolest dwarf to date for which a similar or less luminous companion has been detected.

The proper motion measured for DENIS-P J0205, 0.442″ at PA 82.6° (Table 1), is directed almost entirely along the 92° PA derived for the binary and would have produced a total motion of about 0.6″ in the $\sim$ 1.5 years between observations reported here. This is greater than the binary separation itself, which is measured consistently at both epochs to be 0.51″. Relative to 3 background stars detected in our field of view, we measure the total proper motion of the system to be 0.58 ± 0.22″ along PA 77 ± 7°

between epochs. Consequently, it is securely established that DENIS-P J0205 comprises a common-proper-motion pair. The trigonometric parallax, 0.0555±0.0023, implies a distance of 18 pc, similar to that of DENIS-P J1228, and a projected separation of 9.2 AU for the binary components.

2MASSW J1146

The lithium dwarf, 2MASSW J1146, is classified L3 V. With a trigonometric parallax $\pi = 0.0382{\pm}0.0013''$, it is the most distant of the three (D = 26.2 pc). Its angular separation, $0.29 \pm 0.06''$ at PA $206 \pm 19°$, implies a projected distance of 7.6 AU. It has the smallest proper motion of the three, $0.097''$ at PA 20.2°, but in a direction that is nearly anti-parallel to the PA of binary separation. Consequently, differential proper motion would have been easily detected after the nearly 1-year interval separating our observations. Second-epoch observations had relatively poor seeing; the resulting scatter in Fig. 2 is evident. Nevertheless, the results still cluster about a mean coincident with that obtained at the earlier epoch, indicating common proper motion.

For 2MASSW J1146, a second set of images was acquired in the first epoch using NIRC'S "CH_4" filter centered at $\lambda_{eff} = 2.269$ μm with $\Delta\lambda = 0.155\mu$m. Binary separation and PA estimates from fits to these data are averaged into the results reported above. Since the CH_4 flux component ratio agrees with the K-band ratios, within the uncertainties, we report here the average of all three: 1.0±0.4. The absence of any difference precludes a contrasting presence of CH_4 absorption in one of the components, as expected for a luminosity ratio of 1.

4. Discussion

The three binary systems presented here have similar projected separations (5 to 9 AU) and luminosity ratios near unity. They represent the first binary detections in preliminary analysis of a larger dual-epoch survey in which only 10 L-dwarf images have been completely analyzed in two epochs. No companions with wider separation or more highly contrasting luminosities have been found thus far. Although analysis of our complete sample is required to make unassailable statements about the L dwarf binary distribution, these preliminary results suggest a conjecture for further testing: namely, that multiple systems are not uncommon in the L dwarf population, that their distribution peaks at radial separations like that of both Jovian planets in our solar system and binary stars generally ($\sim 5 - 30$ AU), and that low-contrast mass ratios are common. The latter claim is especially in need of testing, since our survey is not very sensitive to companions at the separations reported here if they have high luminosity contrast ratios. Further, the magnitude-limited surveys from which our sample is taken are biased toward the detection of equal-luminosity binaries, since their combined luminosity is greater than for single stars of the same spectral type. Ultimately, techniques with both high resolution and high dynamic range must be applied to a volume-limited sample to reliably identify the distribution of circumstellar bodies that encircle the members of this population of very cool objects.

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Fig. 1.— a) Contour plot of K-band imaging of DENIS-P J1228 together with that of Kelu-1, the “psf” star used to derive binary component parameters. Contours are at logarithmic intervals. Crosses mark the separation and PA of components derived in the psf fits to the data shown here. b) Plots as in a) for DENIS-P J0205 and associated psf star, LP 647-13, c) Plots as in a) and b) for 2MASSW J1146 and psf star 2MASSW J1145.

Fig. 2.— Binary separation and position angle from psf-fits of individual frames for 2MASSW J1146 (small open circles), DENIS-P J1228 (small open triangles), and DENIS-P J0205 (small filled triangles). The mean of each of the measurements is plotted as a large open symbol for each object with error bars that mark the rms deviation about the mean. The HST/NICMOS result for DENIS-P J1228 is plotted as an open diamond.

Fig. 3.— Histograms of the best-fit values of the flux component ratio. Data for all epochs are plotted together as open bars. The subset of measurements from the epoch with best seeing is plotted as hashed bars. Component ratios are for B/A. For DENIS-P J1228, the identification of the primary is taken from Martín et al. (1999) at shorter wavelengths.

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Table 1.

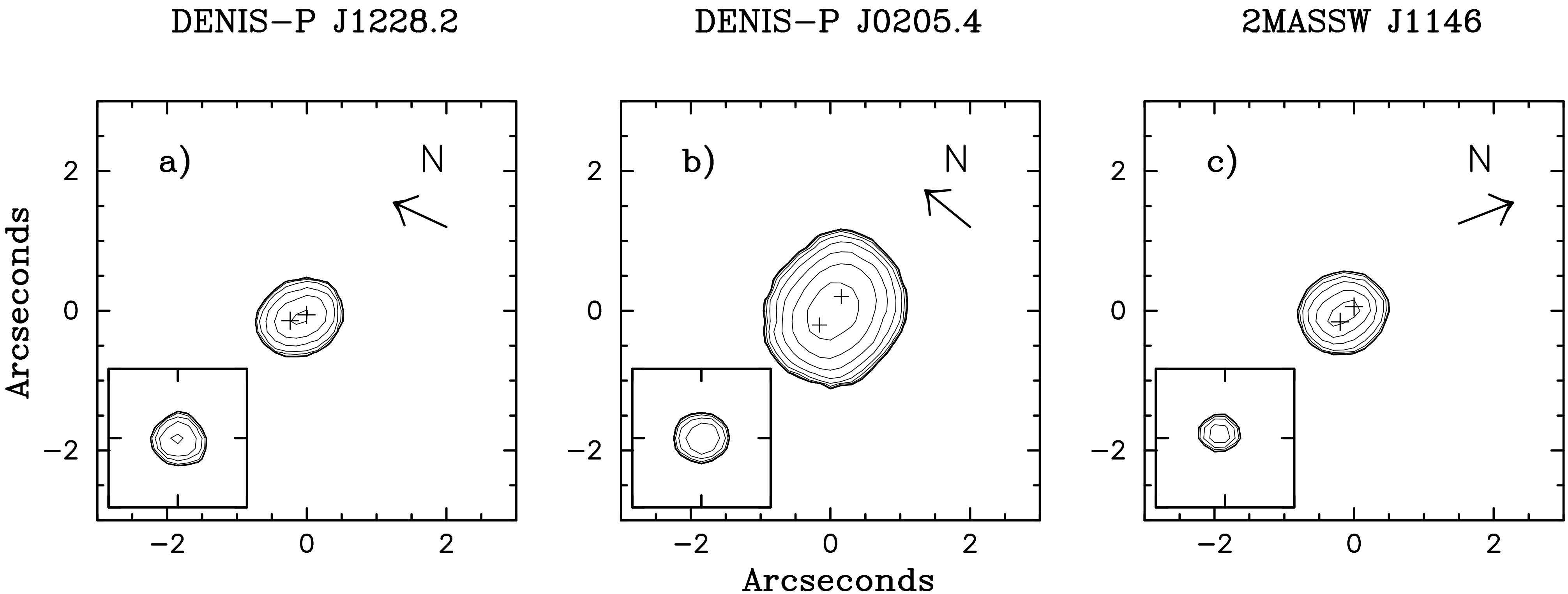
Name	α (J2000)	δ (J2000)	Sp T	K_s	$\pi_{trig}('')^1$	$\mu('')/\mathrm{yr}^1$	$\theta(\mathrm{deg})^1$
DENIS-P J0205	$02^h05^m29.47^s$	$-11^\circ\ 59'\ 29.6''$	L7 V	12.99±0.04	0.0555±0.0023	0.442	82.6
LP 647-13	$01^h09^m50.90^s$	$-03^\circ\ 43'\ 26.0''$	M9 V	–	–	0.359	85
LHS 2351	$10^h16^m35.00^s$	$+27^\circ\ 51'\ 48.0''$	M8 V	11.34±0.04	0.0461±0.0031	0.49	318.5
2MASSW J1145	$11^h45^m57.20^s$	$+23^\circ\ 17'\ 30.0''$	L1.5 V	13.87±0.08	–	–	–
2MASSW J1146	$11^h46^m34.50^s$	$+22^\circ\ 30'\ 53.0''$	L3 V	12.63±0.04	0.0382±0.0013	0.097	20.2
DENIS-P J1228	$12^h28^m13.80^s$	$-15^\circ\ 47'\ 11.0''$	L5 V	12.81±0.03	0.0553±0.0029	0.21	143.8
KELU-1	$13^h05^m40.20^s$	$-25^\circ\ 41'\ 06.0''$	L2 V	11.81±0.03	0.0516±0.0022	0.294	270.6

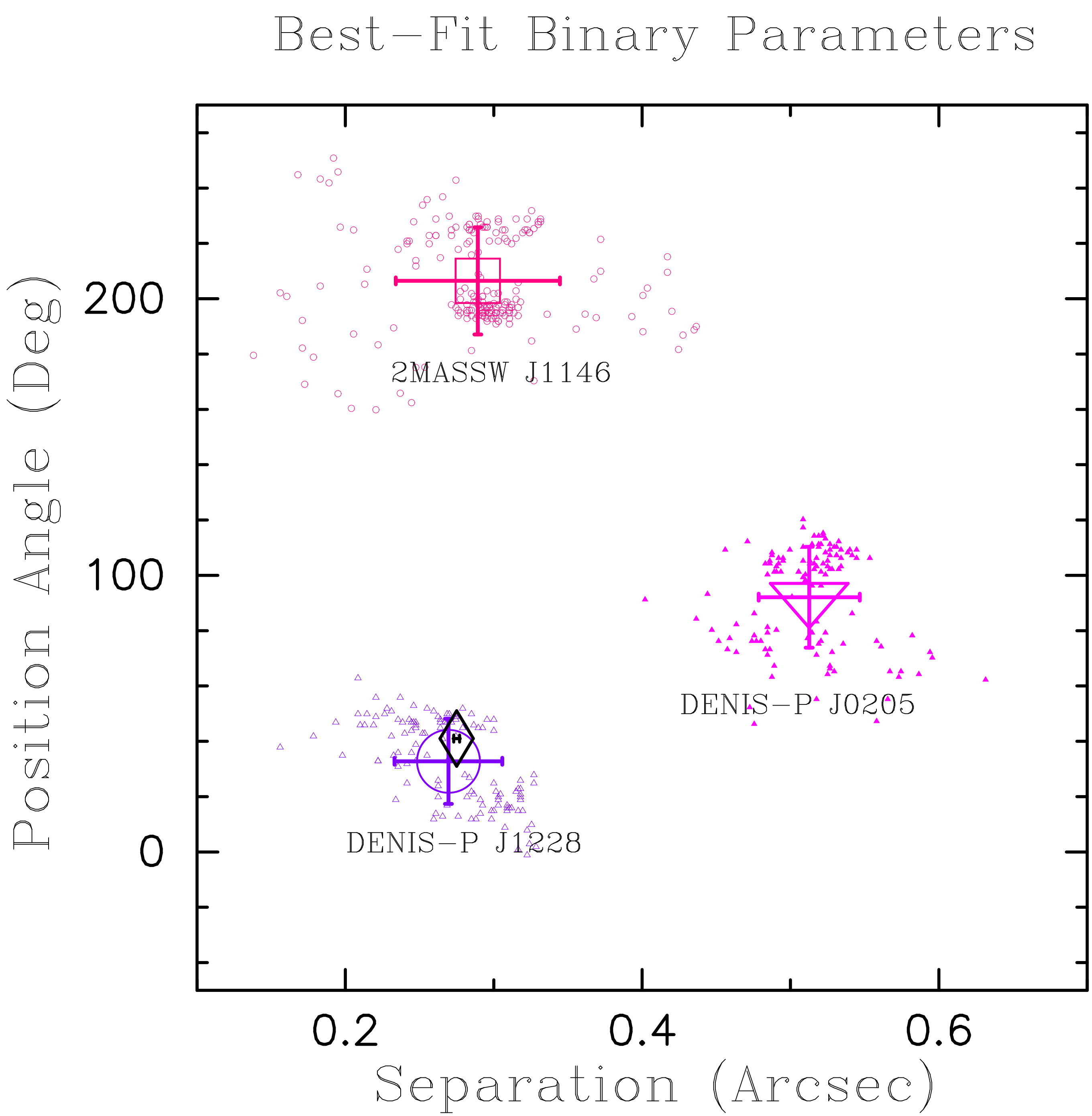
References. — (1) Dahn et al. (1999)

Table 2. PSF Fitting Results

Object	Date Observed	PSF STAR	PSF FWHM	Sep (arcsec)	PA (deg)	Flux Ratio
DENIS-P J0205	29Jul97	LP 647-13	$0.33''$	0.51 ± 0.02	106±5	0.99 ± 0.08
DENIS-P J0205	24Jan99	LP 647-13	$0.45''$	0.51 ± 0.04	72±10	1.00 ± 0.26
2MASSW J1146	14Feb98	2MASSW J1145	$0.24''$	0.30 ± 0.01	196±3	0.87 ± 0.07
2MASSW J1146[a]	16Feb98	2MASSW J1145	$0.36''$	0.28 ± 0.03	225±10	1.03 ± 0.20
2MASSW J1146	24Jan99	LHS 2243	$0.40''$	0.29 ± 0.10	197±24	0.98 ± 0.47
DENIS-P J1228	14Feb98	Kelu-1	$0.25''$	0.25 ± 0.02	45±6	1.28 ± 0.50
DENIS-P J1228	09Feb99	Kelu-1	$0.28''$	0.30 ± 0.02	17±7	0.99 ± 0.25

[a]These observations were taken in NIRC's CH_4 filter centered at $\lambda_{eff} = 2.269$ μm with $\Delta\lambda = 0.155\mu$m.


DENIS−P J1228.2
DENIS−P J0205.4
2MASSW J1146
a)
b)
c)
N
N
N
Arcseconds
Arcseconds
2
0
−2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DENIS-P J1228
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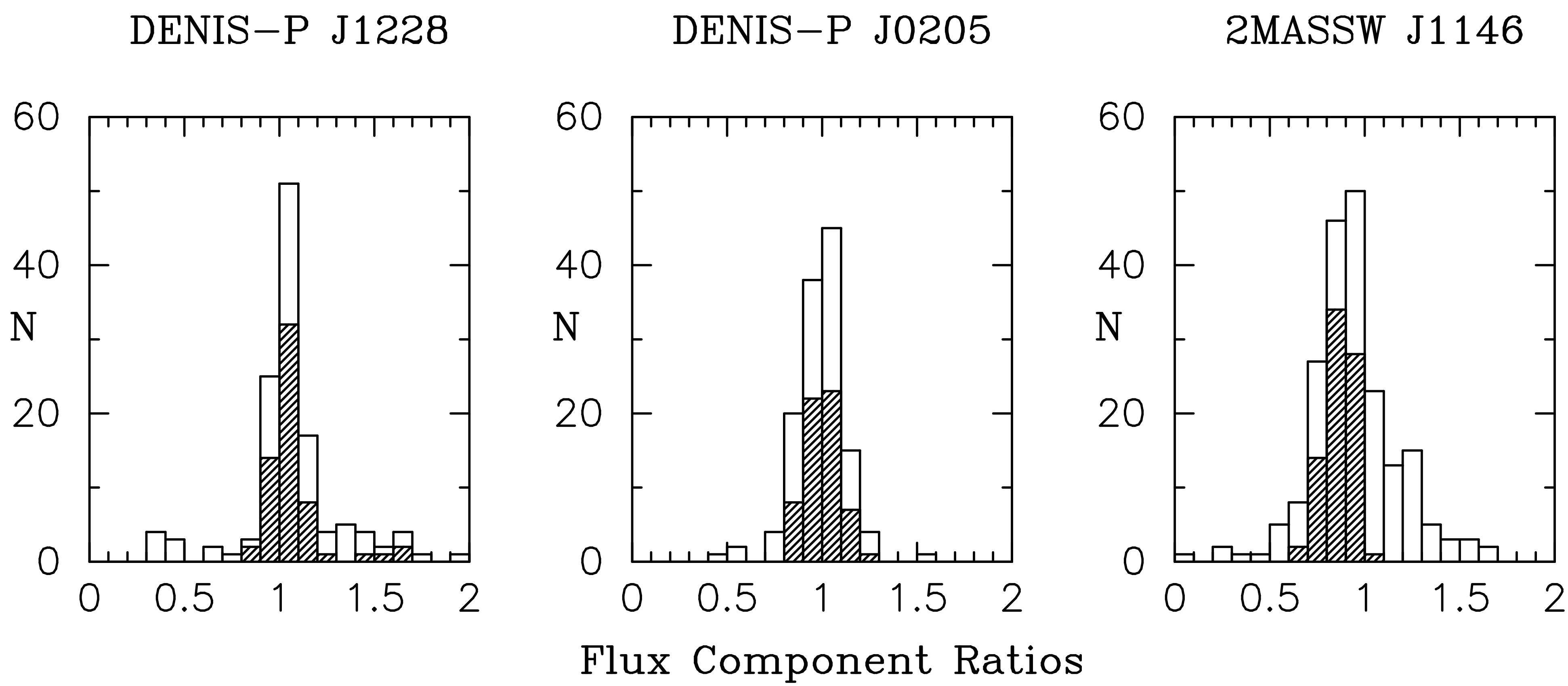
0.6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2MASSW J1146
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20
40
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0
0.5
1
1.5
2
Flux Component Ratios